Age-structured production model assessments and projections including updated parameters to model the intermittent aggregation of Namibian orange roughy

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Abstract

Updated assessments of the four orange roughy aggregations off Namibia, based upon a maximum penalised likelihood approach which uses all available indices of abundance and reflects the proportion of a stock present at the fishing aggregation each year, are presented, and projections under constant catch levels reported. Further abundance data now available for *Frankies* allow the parameters of the beta distribution used to reflect the proportion aggregating to spawn each year to be updated. This leads to more optimistic results for stock status, slightly so for *Frankies* and *Rix* for which estimates of the ratio of current to pre-exploration levels increase from the 60%'s to the 70%'s, but substantially so for *Johnies* which is no longer estimated to be heavily depleted. With no new standardised CPUE values available, *Hotspot* remains estimated as highly depleted. The range of variable aggregation levels estimated are not qualitatively incompatible with information for Australian orange roughy aggregations. Changing from the earlier to the updated beta distribution parameters increases medium term annual sustainable yield estimates for the resource as a whole from 1 850 to 4 400 tons, though the latter figure needs to be considered with caution as it is particularly dependent on the assumption that the beta distribution estimated for proportions aggregating at *Frankies* applies also to *Johnies*. Broadly speaking, MSY estimates at 1 600 to 3 500 tons are some 5–60% more than estimated a year previously. However, the varying proportions of abundance present at aggregations from year to year would lead to difficulties in making a catch of this size every year.

Introduction

This paper updates assessments of the orange roughy resource at the various aggregations off Namibia presented by Brandão and Butterworth (2006), based upon a maximum penalised likelihood estimation approach that allows for the possibility of annually variable levels of aggregation of the stocks in the fishing areas. The standardised CPUE series obtained by the "zero" method of dealing with missing abundance indices in some years in sub-aggregations as presented by Brandão and Butterworth (2006) is used for input. All available indices of abundance are taken into account, and deterministic projections under various levels of constant catch are reported.

Brandão and Butterworth (2003) used the signal (an index of abundance for 2002 that is in the region of the 1997 estimate) observed in the hydroacoustic abundance index for *Frankies* in 2002 to model variable aggregation of the orange roughy stock, without having to assume that $x_{1997} = 1$ (i.e. that there was 100% presence of spawning fish on the aggregation at the time of the survey that year). A beta distribution penalty function was also applied to the proportion of stock present (x_y) in the model for variable aggregation. The procedure undertaken by Brandão and Butterworth (2003) to determine the fixed mean (μ_x) and standard deviation (σ_x) values used to specify the α and β parameter values of the beta distribution is re-evaluated using the additional acoustic abundance indices now available for *Frankies*.

Data

In the analyses presented in this paper a "fishing year" has been taken to be the period July to June as first proposed by Brandão and Butterworth (2002a).

Table 1 shows the total annual ("fishing year") landed catches of orange roughy for the different aggregations.

The uncorrected and corrected hydroacoustic abundance (I. Hampton, pers. commn) and research swept area indices are listed in Table 2. In 2000 the *Emanguluko* (instead of the *Southern Aquarius*) performed the research swept area survey; therefore the research swept area value for 2000 was corrected for a vessel effect (obtained from the General Linear Model applied to the commercial CPUE data), and this corrected value is used in all the assessments in this paper. The hydroacoustic survey abundance estimates for *Frankies* in 2004 and 2005 reported now differ from those given in the previous year. Both sets of estimates are shown in Table 2. The hydroacoustic survey estimate for *Rix* in 2005 has now been omitted from a survey report kindly provided by R. Cloete (pers. commn). This value has been kept in Table 2.

The standardised commercial CPUE data obtained when fitting a delta-lognormal model and applying the "zero" method of dealing with missing abundance indices in some years in sub-aggregations (Brandão and Butterworth, 2007) are given in Table 3.

The biological parameters used in the assessment are shown in Table 4. Note that different values are used for the *Hotspot* aggregation, as these are considered more appropriate for the larger orange roughy which occur there.

Methods

Bias Factor Uncertainties

Appendix 1 lists the various bias factor distributions obtained from Boyer and Hampton (2001) that are appropriate to the acoustic estimates for each of the three aggregations where such surveys have taken place. The method of obtaining the bias q (and its uncertainty) in the relationship:

$$I_y = q\ B_y \tag{1}$$

where I is the corrected hydroacoustic estimate of abundance, and B is the true resource biomass (the recruited = mature component thereof, in terms of the population model of Appendix 2) as explained in Brandão and Butterworth (2000). The one difference here is that the input data have now been standardised so that the same bias factor distributions apply for all years.

Population Model Fitting

The fundamental ASPM methodology applied is as in Brandão and Butterworth (2003) (see Appendix 2), and the basic biological parameter values remain unchanged, except that more appropriate biological parameters for the *Hotspot* aggregation have been used (see Table 4). Brandão and Butterworth (2004) concluded that given the 2002 acoustic survey result at *Frankies* (Table 2), the premise that fishing down was the primary cause of the earlier drop in CPUE and other indices in at least this aggregation can no longer stand, and therefore that the intermittent aggregation model seemed the best basis upon which to provide advice. For this reason, this paper concentrates only on the assessment of the Namibian orange roughy resource under the intermittent model.

Results and Discussion

Table 5 gives the values of quantities input to equations (A2.20 to A2.22) for the fitting process, including the values of the parameters of the lognormal distributions used to approximate the systematic and random uncertainty factors in the hydroacoustic estimates of abundance.

Brandão and Butterworth (2003) introduced a new variable aggregation model including a year aggregation factor x_y (all estimated by the model) with a penalty on x_y corresponding to the assumption that these values follow a beta distribution. The signal in the hydroacoustic index of abundance for 2002 of *Frankies* that is in the region of the 1997 estimate was used to inform this variable aggregation model of the orange roughy stock, without having to assume that x_{1997} = 1. As the x_y proportions lie between 0 and 1, a beta distribution penalty function which is restricted to this range was applied to the x_y proportions. Brandão and Butterworth (2003) applied various fixed mean (μ_x) and standard deviation (σ_x) values to specify the α and β parameter values of the beta distribution penalty, and results were obtained for the *Frankies* aggregation. From these results, a set of values (μ_x, σ_x) were chosen that satisfied the condition that more than 80% of the stock was present in 1997 (x_{1997} > 0.8) and the negative of the log-likelihood function was examined. From this set three options of (μ_x, σ_x) were chosen that spanned a range of stock depletion: most, mid and least depletion. This set of three values for (μ_x, σ_x) was then assumed to apply to the other aggregations as well. Brandão and Butterworth (2004) assumed the mid-depletion option for (μ_x, σ_x), i.e. μ_x = 0.6 and σ_x = 0.2 and all subsequent stock assessments have used these values.

The procedure to fix values for (μ_x, σ_x) is repeated in this paper using the extra abundance indices now available for *Frankies*. Table 6 shows the negative log-likelihood and the x_{1997} estimate for various values of (μ_x, σ_x) applied to the *Frankies* aggregation. Other values for (μ_x, σ_x) were also examined but in some cases model convergence became a problem. The values of μ_x = 0.5 and σ_x = 0.25 meet the criterion of more than 80% of the stock present in 1997 and has the lowest negative log-likelihood value. The values for (μ_x, σ_x) previously used in assessments (i.e. μ_x = 0.6 and σ_x = 0.2) are the least favoured in terms of model selection (having the highest negative log-likelihood value) amongst all those shown in Table 6. Figure 1 shows the form of the beta distribution for three sets of values for (μ_x, σ_x) used in the stock assessment of orange roughy in the paper.

Tables 7 to 10 provide results for the population model fitting exercises for the four aggregations, *Johnies*, *Frankies*, *Rix* and *Hotspot*. Results are for the intermittent aggregation model which includes year aggregation factors x_y (all estimated by the model), with a penalty on x_y corresponding to the assumption that these values follow a beta distribution. The chosen values for the mean (μ_x) and standard deviation (σ_x) values to specify the α and β parameter values of the beta distribution penalty included in the variable aggregation model are: the same as used previously (viz. μ_x = 0.6 and σ_x = 0.2; referred to as the “Old” basecase), the values that provide the lowest negative log-likelihood but meeting the criterion that x_{1997} > 0.8 (viz. μ_x = 0.5 and σ_x = 0.25; referred to as the “New” basecase) and as a sensitivity test, the values for (μ_x, σ_x) that meets the criterion that x_{1997} > 0.9 (as shown by the “Old” basecase (μ_x, σ_x) values) (viz. μ_x = 0.55 and σ_x = 0.25; referred to as the “Alternative” case). When fitting the variable aggregation model to the Rix aggregation with the new values for (μ_x, σ_x), the σ^{CPUE} value is fixed at 0.6 (the same as that estimated with the old values for (μ_x, σ_x) and similar to that estimated for *Johnies*) rather than estimated, to offset a tendency by the model to overweight the CPUE data. All models are fitted to the baseline CPUE interpretation only (i.e. applied to the standardised CPUE series obtained from the “zero” method).

The stock depletion at the beginning of the fishing year 2006 for *Johnies* is estimated at 12% of the pre-exploitation abundance (Table 7) for the “Old” basecase. These results are similar to those obtained in the previous year’s assessment when more weight was given to the CPUE results than the hydroacoustic abundance indices. When the new values for (μ_x, σ_x) are used, the current depletion is estimated at 74–77%, i.e. closer to that estimated previously when fixing q^{AC} to be 1.07 (both the “New” basecase and the “Alternative” case estimate a value for q^{AC} close to this value). The proportion of the stock present in 1997 is estimated to be in the region of 89–95%, while the “Old” basecase estimates 18% to have aggregated in 2006, and both the “New” and the “Alternative” models estimate that only 3% aggregated in 2006.

The hydroacoustic survey estimates of abundance for *Frankies* in 2004 and 2005 have changed from those previously reported (see Table 2). As a sensitivity test, the “Old” basecase model was run with both the old and the new survey estimates of abundance for 2004 and 2005. There were minimal changes in the results (Table 8) and therefore further analyses were carried out with the new acoustic survey abundance indices. The stock depletion at the beginning of the fishing year 2006 for the *Frankies* aggregation is estimated in the region of 64–65% of the pre-exploitation abundance under the “Old” basecase for both sets of acoustic survey abundance estimates (Table 8). Similar results are obtained for the “New” basecase and the “Alternative” case, with the “Alternative” case giving very slightly more pessimistic values for the stock status. The “New” basecase estimates the stock depletion to be at 76% of the pre-exploitation abundance and that in 1997 80% of the stock aggregated, with 63% aggregated in 2002 but only 22% aggregated in 2006.

The hydroacoustic survey estimate of abundance for *Rix* aggregation in 2005 previously reported has been omitted from the most recent survey report (see Table 2). As a sensitivity test, the “Old” basecase model was run with this estimate included and omitted from the data. There were minimal changes in the results (Table 9) and therefore further analyses were carried out without this acoustic survey abundance index. The stock depletion at the beginning of the fishing year 2006 is estimated at 58 – 65% of the pre-exploitation biomass under the “Old” basecase for both when the 2005 survey index is omitted or included in the model (Table 9). Convergence problems were encountered when the “New” and “Alternative” models were fitted. To offset a tendency by the models to overweight the CPUE data, the σ^{CPUE} value was fixed to 0.6 (as estimated by the “Old” basecase). Similar results are obtained for the “New” basecase and the “Alternative” case, with the “Alternative” case giving slightly more pessimistic values for the stock status (stock depletion is estimated to be at 78% of pre-exploitation abundance under the “New” basecase and at 74% under the “Alternative” case). The “Old” basecase (with new survey abundance indices) estimates that for most years more than 50% of the stock aggregated in *Rix* prior to 2001. Since 2001, however, less than 50% of the stock has aggregated with only 20% aggregating in 2003. However, both the “Alternative” and “New” models estimate that in all years, except 1997 (and 1998 for the “Alternative” model), less than 50% of the stock aggregated, and in most years less than 20% of the stock aggregated.

The choice of values for (μ_x, σ_x) makes little difference to the results for the *Hotspot* aggregation (Table 10). The stock depletion at the beginning of the fishing year 2006 for the *Hotspot* aggregation is estimated at 10% of the initial biomass. The extent of aggregation estimated varies between 52% and 80%. Problems were encountered with convergence issues for *Hotspot* in that the stringent criterion for convergence was not quite met. Due to the lateness of the acquisition of the data, there was not enough time to try to resolve this issue; in any case, as the results obtained were in the region of those reported previously, pursuit of better convergence was not seen as a priority.

Note that the *Hotspot* aggregation is the only one for which no survey estimates, and in particular no hydroacoustic estimates (see Table 2), are available, so that these assessment results are based entirely on the trend shown by the CPUE data. The pattern of results for the other aggregations suggests that the CPUE data are over-estimating the extent of decline, and therefore that this assessment of the status of the *Hotspot* aggregation may be overly pessimistic.

Figures 2 to 5 show the observed and predicted values for each of the available indices of abundance of orange roughy for each of the aggregations. Results shown are for the intermittent aggregation model for the “Old” and “New” basecases (for the Frankies and Rix aggregations, results are shown for the new survey abundance indices). For the *Johnies* aggregation, the “Old” basecase model does not provide a particularly good fit to the first (1997) observation in the hydroacoustic survey and the research swept area abundance indices, nor the 1994 CPUE index. For the “New” basecase, fits to the acoustic and research trawl surveys are greatly improved, but that to the CPUE series deteriorates. For *Frankies* the “Old” basecase model struggles somewhat to fit the acoustic index for 1997 and 2002, and the 1997 research swept area index. The fit to the CPUE series is not very good. The “New” basecase model shows an improved fit to all available indices of abundance. The same is observed for the *Rix* aggregation. For *Hotspot* the models (both “Old” and “New” basecase models) fit the CPUE index for the later years reasonably, but not that for the first year.

Figures 6 to 9 show 35-year deterministic projections of the orange roughy stock for each of the aggregations under the intermittent model for the “Old” and “New” basecase models. For the *Johnies* aggregation a 250 t constant catch improves the stock depletion from 12% to 21% whereas a zero constant catch improves the stock depletion after 35-years to 56% of the pre-exploitation abundance under the “Old” basecase model. However, if the new values of $\mu_x = 0.5$ and $\sigma_x = 0.25$ are used (i.e. the “New” basecase model), results are much more optimistic (Figure 6b) with a constant catch of 1 000 t reduces the stock depletion from 74% to 64%. For the *Frankies* aggregation, a constant catch of 500 t makes hardly any change to stock depletion (from 65 to 63%), but this is reduced to 34% of pre-exploitation abundance under a 1 000 t constant catch under the “Old” basecase model (Figure 7a). Under the “New” basecase model a 500 t constant catch makes no difference to the stock depletion (76%), and a constant catch of 1 000 t reduces the stock to 57% of the pre-exploitation abundance (Figure 7b).

Deterministic projections under the “Old” basecase model for the *Rix* aggregation (Figure 8a) show a reduction of the stock to 50% (from 65%) of initial biomass under a constant catch of 500 t for 35 years and to 29% under a constant catch of 750 t. For the “New” basecase model, a constant catch of 500 t for 35 years reduces the stock to 69% (from 78%) and to 57% of the pre-exploitable biomass under a constant catch of 750 t. For the *Hotspot* aggregation, a constant catch of 50 t improves the stock depletion to 41% from 10% of initial biomass, but to only 18% for a constant catch of 100 t. If no catches are taken for 35-years, the resource improves from a depletion of 10% of initial biomass to 63%.

While the intermittent aggregation hypothesis provides a basis to reconcile abundance index data from various sources for the Namibian orange roughy aggregations, there remain two concerns with the current analyses. First they depend on extrapolating the beta distribution for the proportion aggregating that is fit to the data for *Frankies* to the other aggregations, and secondly the resultant assessments suggest the proportions aggregating which at times drop as far as 10% and even below.

Since the current status assessed for *Johnies* in particular depends heavily on such low levels of aggregation in certain years, information on other orange roughy fisheries has been sought to ascertain whether they show evidence of similar behaviour. Tony Smith and Sally Wayte of CSIRO, Australia have kindly brought to our attention regarding Australian roughy resources:

i) large variations in the proportion of the population at St Helens Hill (15% in 1999 and 88% in 2006), thought this may be linked to interchange from the nearby St Patricks Head aggregation, and also perhaps to fishing disturbance (St Helens Hill having been closed since 2003 while St Patricks has been fished only recently); and
ii) proportions of roughy spawning in the Eastern Zone which varied over 54–72% during the period 1989 to 1992.

Tony Smith (pers. commn) further advises that for Australian orange roughy stocks overall, despite evidence of considerable interannual variation, it is still not possible to distinguish between the alternative hypotheses of:

a) a variable fraction of the entire stock spawning from year to year (cf: the intermittent aggregation approach above);
b) variations in spawning locations from year to year (with perhaps some spawning sites still to be located); and
c) failure for the survey to correspond to the time of peak spawning from year to year, with evidence of movement on and off spawning sites at very short time scales (hours to days) which suggests that surveys can easily miss peak periods of aggregation.

While this information does not specifically confirm the estimates of aggregation proportions for Namibian aggregations developed in this paper, it is sufficient to indicate that they are not implausible. This is comforting, as the alternative approach of assuming abundance directly proportional to CPUE is impossible to reconcile with past catch histories and estimates of abundance in absolute terms from the acoustic surveys of these aggregations.

Conclusions

Table 11 presents a summary based on the baseline results for the intermittent aggregation model. This indicates two of the major aggregations (*Frankies* and *Rix*) to be reasonably healthy and in the 60/70%s of their initial abundances, but *Hotspot* at about 10% to be well below MSYL. Estimates for *Johnies* range between these two extremes, with acoustic and swept area survey results favouring the more optimistic interpretation, and CPUE data the more pessimistic. Depending on these alternative interpretations for *Johnies*, the combined MSY estimates range from about 1 600 ("Old" basecase) to 3 500 tons ("New" basecase), which are respectively some 5% to 60% more than estimated a year previously by Brandão and Butterworth (2006).

Projections using the intermittent aggregation model suggest an appropriate overall annual catch in the medium term to be in the vicinity of 1 850 to 4 400 tons, again depending on the interpretation for *Johnies*. It is important, though, to bear in mind that the intermittent aggregation effect suggests that in some years the extent of aggregation in the fishing areas will not be sufficient for such a level of catch to be made.

The more optimistic “New” basecase results of this paper need to be considered with caution. They rest on the update of the beta distribution parameters for the proportion aggregating at *Frankies* given further data, and the assumption that this applies also to the other aggregations (*Johnies* in particular, for which the results are particularly sensitive to this assumption). Nevertheless in qualitative terms, information for Australian orange roughy aggregations is such as to suggest that these updated results are not implausible.

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Table 1. Yearly (fishing year) catches of orange roughy (in tons) taken from the aggregations considered in this paper. The notation of, for example, "1996" for year refers to the period July 1996 to June 1997. The fishing year 2006 is incomplete as data were available only until December 2006.

Year	*Johnies*	*Frankies*	*Rix*	*Hotspot*	Total
1994	1 145	—	—	2 169	3 315
1995	3 773	2 291	323	897	7 284
1996	2 062	8 736	1 861	477	13 136
1997	7 539	4 817	3 836	482	16 675
1998	1 917	650	3 921	358	6 845
1999	1 367	40†	444	226	2 076
2000	667	11†	307	224	1 209
2001	452	214†	183	106	955
2002	376	155††	350	336	1 217
2003	430	158††	124	129	841
2004	122	67††	13†††	60	262
2005	135	0	0†††	30	165
2006	199	67	0†††	12	278

† Closed to normal commercial fishing

†† Fishery partially reopened since September 2002

††† Closed to normal commercial fishing on 1st August 2004

Table 2. Abundance indices of orange roughy obtained from hydroacoustic surveys and research swept area surveys for the aggregations considered in this paper.

a) Target acoustic indices (uncorrected for biases) of absolute abundance in tons (CV). Note that these CV's correspond to the survey sampling variability only. These results are all given as standardised to the *Welwitchia*, against which the vessels that carried out the surveys have been calibrated.

Year	***Johnies***	***Frankies (previous values)***	***Frankies (recent values)***	***Rix***	**Survey vessel**
1997	34 178 (0.21)	17 925 (0.25)	17 925 (0.25)	21 579 (0.15)	*Nansen*
1998	3 570 (0.43)	4 940 (0.38)	4 940 (0.38)	7 572 (0.19)	*Nansen*
1999	—	1 782 (0.25)	1 782 (0.25)	—	*Nansen*
2000	—	3 756 (0.30)	3 756 (0.30)	—	*Conbaroya*
2001	—	4 820 (0.16)	4 820 (0.16)	—	*Southern Aquarius*
2002	—	15 802 (0.21)	15 802 (0.21)	—	*Southern Aquarius*
2003	—	6 133 (0.27)	6 133 (0.27)	1 174 (0.51)	*Southern Aquarius*
2004	—	4 066 (0.27)	3 727 (0.26)	—	*Conbaroya Quarto*
2005	—	4 817 (0.47)	7 734 (0.47)	2 104* (0.31)	*Conbaroya Quarto*
2006	—	4 914 (0.27)	4 914 (0.27)	2 422 (0.64)	*Southern Aquarius*

***** The 2005 acoustic index has been omitted from the most recent survey report kindly provided by R. Cloete (pers. commn).

Table 2 cont. Abundance indices of orange roughy obtained from hydroacoustic surveys and research swept area surveys for the aggregations considered in this paper.

b) Target acoustic indices (corrected for biases) of absolute abundance in tons (CV). Note that these CV's incorporate uncertainties in the survey bias factors as well as the survey sampling variability.

Year	*Johnies*	*Frankies (previous values)*	*Frankies (recent values)*	*Rix*
1997	55 757 (0.35)	29 567 (0.38)	29 567 (0.38)	34 872 (0.32)
1998	6 267 (0.54)	8 478 (0.49)	8 478 (0.49)	12 301 (0.35)
1999	—	2 934 (0.38)	2 934 (0.38)	—
2000	—	6 294 (0.44)	6 294 (0.44)	—
2001	—	7 805 (0.34)	7 805 (0.34)	—
2002	—	25 839 (0.37)	25 839 (0.37)	—
2003	—	10 126 (0.41)	10 126 (0.41)	2 133 (0.63)
2004	—	6 720 (0.41)	6 158 (0.41)	—
2005	—	8 667 (0.59)	13 916 (0.59)	3 514 (0.43)
2006	—	8 176 (0.41)	8 176 (0.41)	4 731 (0.77)

c) Research swept area indices of relative abundance (CV), standardised for the *Southern Aquarius*.

Year	*Johnies*	*Frankies*	*Rix*	Survey vessel
1997	57 650 (0.27)	30 995 (0.37)	—	*Southern Aquarius*
1998	6 980 (0.25)	2 400 (0.60)	—	*Southern Aquarius*
1999	2 137 (0.40)	3 055 (0.35)	1 006 (0.59)	*Southern Aquarius*
2000	4 365 (0.35)	—	—	
2000 (uncorrected for vessel effect)	3 330 (0.34)	—	—	*Emanguluko*
2001	11 544 (0.46)	—	—	*Southern Aquarius*
2002	10 148 (0.59)	—	—	*Southern Aquarius*
2003	943 (0.18)	—	—	*Southern Aquarius*
2004	5 865* (0.73)	—	—	*Conbaroya Quarto*
2005	2 132* (0.64)	—	—	*Conbaroya Quarto*
2006	1 117 (0.16)	—	—	*Southern Aquarius*

***** The 2004 and 2005 swept area indices have not been corrected for a vessel effect at the present time in a similar way that the 2000 index was.

Table 3. Standardised commercial CPUE indices of relative abundance (normalised to their mean) for orange roughy obtained from standardised commercial CPUE series, based on a delta-lognormal model, for the aggregations considered in this paper. The “zero” method (see Brandão and Butterworth (2002b) for a description of the method) of dealing with cells (sub-aggregations) without data in particular years is considered.

Year	*Johnies*	*Frankies*	*Rix*	*Hotspot*
1994	6.411	—		6.236
1995	1.006	1.354	0.518	1.815
1996	1.382	4.797	0.676	0.941
1997	1.827	1.499	4.415	0.333
1998	0.662	0.715	1.914	0.524
1999	0.296	0.325	0.379	0.277
2000	0.256	—	0.393	0.110
2001	0.142	0.474	0.280	0.178
2002	0.179	0.167	0.282	0.378
2003	0.151	0.474	0.144	0.099
2004	0.067	0.024	—	0.109
2005	0.456	—	—	—
2006	0.166	0.171	—	—

Table 4. Biological parameter values assumed for the assessments conducted. Note that for simplicity, maturity is assumed to be knife-edge in age.

Parameter	Value	
	***Johnies*, *Frankies* and *Rix* aggregations**	***Hotspot* aggregation**
von Bertalanffy growth		
ℓ_∞ (cm)	29.5	37.2
κ (yr^{-1})	0.069	0.065
t_0 (yr)	-2.0	-0.5
Weight length relationship		
a (gm/cm^b)	0.1354	0.1354
b	2.565	2.565
Age at maturity (yr)	23	29
Steepness parameter (h)	0.75	0.75

Table 5. Parameters of distributions contributing to the various terms in the negative log likelihood of equations (A2.20) and (A2.22).

Factor	Central value	Standard deviation
Natural mortality	$M^{est} = 0.055$	$\sigma_M = 0.30$
x_y penalty function	$\mu_x = 0.6$	$\sigma_x = 0.2$
q^{AC}-systematic	$q^{est} = 1.0$	$\sigma_q^{AC} = 0.22$
q^{AC}-random ***Johnies*** 1997	—	$\sigma_{1997}^{AC} = 0.28$
1998	—	$\sigma_{1998}^{AC} = 0.48$
q^{AC}-random ***Frankies*** 1997	—	$\sigma_{1997}^{AC} = 0.31$
1998	—	$\sigma_{1998}^{AC} = 0.44$
1999	—	$\sigma_{1999}^{AC} = 0.31$
2000	—	$\sigma_{2000}^{AC} = 0.38$
2001	—	$\sigma_{2001}^{AC} = 0.26$
2002	—	$\sigma_{2002}^{AC} = 0.29$
2003	—	$\sigma_{2003}^{AC} = 0.35$
2004	—	$\sigma_{2004}^{AC} = 0.35$
2005	—	$\sigma_{2005}^{AC} = 0.55$
2006	—	$\sigma_{2006}^{AC} = 0.35$
q^{AC}-random ***Rix*** 1997	—	$\sigma_{1997}^{AC} = 0.25$
1998	—	$\sigma_{1998}^{AC} = 0.26$
2003	—	$\sigma_{2003}^{AC} = 0.59$
2005	—	$\sigma_{2006}^{AC} = 0.37$
2006	—	$\sigma_{2006}^{AC} = 0.74$

Table 6. The negative log-likelihood value and the proportion of stock present at the *Frankies* aggregation in 1997 (x_{1997}) for various values of the mean (μ_x) and the standard deviation (σ_x) of the beta distribution that is applied to the penalty function of the proportion of stock present. Results are shown when the "new" acoustic surveys estimates for the *Frankies* aggregation are used.

a) Negative log-likelihood value for various values of the mean (μ_x) and the standard deviation (σ_x) of the beta distribution.

μ_x	σ_x	
	0.2	**0.25**
0.45	2.529	2.407
0.5	3.851	3.662
0.55	5.016	4.574
0.6	6.006	5.117

b) Proportion of stock present at the *Frankies* aggregation in 1997 (x_{1997}) for various values of the mean (μ_x) and the standard deviation (σ_x) of the beta distribution.

μ_x	σ_x	
	0.2	**0.25**
0.45	0.725	0.595
0.5	0.796	0.802
0.55	0.851	0.909
0.6	0.898	0.971

Table 7. Estimates obtained when various models are fitted to the available indices of Namibian orange roughy for the *Johnies* aggregation where the standardised CPUE series are obtained using the "zero" method (Brandão and Butterworth 2002b and 2007). The estimates shown are for the pre-exploitation orange roughy (recruited=mature) abundance (B_0), the natural mortality (M), the current stock biomass (B_{2006}) and stock depletion (B_{2006}/B_0) at the beginning of the fishing year 2006, the acoustic estimate multiplicative bias (q^{AC}), the research swept area index multiplicative bias (q^{SA}) and the commercial CPUE index catchability coefficient (q^{CPUE}), the standard deviation for the standardised CPUE series (σ^{CPUE}), the estimated proportion of the stock present each year (x_{1995}, …, x_{2006}), the maximum sustainable yield (MSY), the maximum sustainable yield level (MSYL) and the negative of the log likelihood (as well as its different components). Biomass units are tons.

Parameter estimates	"Old" basecase $(\mu_x = 0.6; \sigma_x = 0.2)$	"New" basecase $(\mu_x = 0.5; \sigma_x = 0.25)$	"Alternative" case $(\mu_x = 0.55; \sigma_x = 0.25)$
B_0	18 252	61 532	55 239
M	0.035	0.049	0.049
B_{2006}	2 102	47 352	41 001
B_{2006}/B_0	0.115	0.770	0.742
q^{AC}	1.8876	0.995	1.013
q^{SA}	3.352	0.940	0.926
q^{CPUE} ($\times 10^5$)	23.061	6.151	5.917
σ^{CPUE}	0.491	0.647	0.670
x_{1994}	0.820	0.818	0.879
x_{1995}	0.360	0.304	0.380
x_{1996}	0.542	0.419	0.521
x_{1997}	0.951	0.891	0.948
x_{1998}	0.565	0.159	0.185
x_{1999}	0.346	0.063	0.075
x_{2000}	0.671	0.103	0.124
x_{2001}	0.795	0.162	0.201
x_{2002}	0.758	0.140	0.176
x_{2003}	0.210	0.024	0.028
x_{2004}	0.411	0.056	0.072
x_{2005}	0.688	0.095	0.115
x_{2006}	0.178	0.027	0.031
MSY	277	1 386	1 231
MSYL	0.250	0.246	0.246
-ln *L*: Total	13.697	4.583	7.354
-ln *L*: CPUE	-2.739	0.832	1.291
-ln *L*: Acoustic survey	6.498	0.193	0.304
-ln *L*: Sweptarea	8.076	2.985	2.984
ln *L*: year bias *x*	-0.900	3.520	5.699
-ln *L*: prior on *M*	-1.957	-2.943	-2.939
-ln *L*: prior on q^{AC}	4.719	-0.005	0.015

Table 8. Estimates obtained when various models are fitted to the available indices of Namibian orange roughy for the *Frankies* aggregation where the standardised CPUE series are obtained using the "zero" method (Brandão and Butterworth 2002b and 2007). The estimates shown are for the pre-exploitation orange roughy (recruited=mature) abundance (B_0), the natural mortality (M), the current stock biomass (B_{2006}) and stock depletion (B_{2006}/B_0) at the beginning of the fishing year 2006, the acoustic estimate multiplicative bias (q^{AC}), the research swept area index multiplicative bias (q^{SA}) and the commercial CPUE index catchability coefficient (q^{CPUE}), the standard deviation for the standardised CPUE series (σ^{CPUE}), the estimated proportion of the stock present each year (x_{1995}, …, x_{2006}), the maximum sustainable yield (MSY), the maximum sustainable yield level (MSYL) and the negative of the log likelihood (as well as its different components). Biomass units are tons.

Parameter estimates	**"Old" basecase (new survey abundance indices)** $(\mu_x = 0.6; \sigma_x = 0.2)$	**"Old" basecase (old survey abundance indices)** $(\mu_x = 0.6; \sigma_x = 0.2)$	**"New" basecase (new survey abundance indices)** $(\mu_x = 0.5; \sigma_x = 0.25)$	**"Alternative" case (new survey abundance indices)** $(\mu_x = 0.55; \sigma_x = 0.25)$
B_0	34 451	33 838	49 851	42 441
M	0.047	0.047	0.050	0.049
B_{2006}	22 452	21 804	38 076	30 612
B_{2006}/B_0	0.652	0.644	0.764	0.721
q^{AC}	1.026	1.028	0.974	0.983
q^{SA}	0.925	0.939	0.781	0.815
q^{CPUE} $(\times 10^5)$	4.094	4.111	3.666	3.724
σ^{CPUE}	1.110	1.130	1.051	1.064
x_{1995}	0.694	0.694	0.587	0.706
x_{1996}	0.766	0.764	0.768	0.845
x_{1997}	0.898	0.901	0.802	0.909
x_{1998}	0.368	0.376	0.203	0.256
x_{1999}	0.178	0.183	0.103	0.129
x_{2000}	—	—	—	—
x_{2001}	0.412	0.423	0.234	0.294
x_{2002}	0.838	0.846	0.627	0.773
x_{2003}	0.523	0.535	0.298	0.376
x_{2004}	0.271	0.302	0.142	0.180
x_{2005}	—	—	—	—
x_{2006}	0.390	0.400	0.216	0.271
MSY	746	728	1 132	953
MSYL	0.246	0.246	0.245	0.246
-ln *L*: Total	6.006	6.294	3.662	4.574
-ln *L*: CPUE	6.043	6.218	5.502	5.619
-ln *L*: Acoustic survey	1.822	2.083	0.601	0.604
-ln *L*: Sweptarea	2.190	2.230	1.197	1.345
ln *L*: year bias *x*	-1.158	-1.354	-0.674	-0.039
-ln *L*: prior on *M*	-2.925	-2.919	-2.944	-2.942
-ln *L*: prior on q^{AC}	0.033	0.035	-0.019	-0.014

Table 9. Estimates obtained when various models are fitted to the available indices of Namibian orange roughy for the *Rix* aggregation where the standardised CPUE series are obtained using the "zero" method (Brandão and Butterworth 2002b and 2007). The estimates shown are for the pre-exploitation orange roughy (recruited=mature) abundance (B_0), the natural mortality (M), the current stock biomass (B_{2006}) and stock depletion (B_{2006}/B_0) at the beginning of the fishing year 2006, the acoustic estimate multiplicative bias (q^{AC}), the research swept area index multiplicative bias (q^{SA}) and the commercial CPUE index catchability coefficient (q^{CPUE}), the standard deviation for the standardised CPUE series (σ^{CPUE}), the estimated proportion of the stock present each year (x_{1995}, …, x_{2006}), the maximum sustainable yield (MSY), the maximum sustainable yield level (MSYL) and the negative of the log likelihood (as well as its different components). Biomass units are tons.

Parameter estimates	"Old" basecase (new survey abundance indices) $(\mu_x = 0.6; \sigma_x = 0.2)$	"Old" basecase (old survey abundance indices) $(\mu_x = 0.6; \sigma_x = 0.2)$	"New" basecase (new survey abundance indices) $(\mu_x = 0.5; \sigma_x = 0.25)$	"Alternative" case (new survey abundance indices) $(\mu_x = 0.55; \sigma_x = 0.25)$
B_0	23 812	20 192	36 417	31 858
M	0.047	0.045	0.050	0.049
B_{2006}	15 478	11 742	28 237	23 655
B_{2006}/B_0	0.650	0.582	0.775	0.743
q^{AC}	1.102	1.186	0.980	0.998
q^{SA}	0.129	0.170	0.195	0.170
q^{CPUE} $(\times 10^5)$	6.335	8.008	8.413	7.697
σ^{CPUE}	0.569	0.528	**0.600**	**0.600**
x_{1995}	0.484	0.447	0.194	0.254
x_{1996}	0.567	0.537	0.251	0.329
x_{1997}	0.929	0.938	0.896	0.948
x_{1998}	0.713	0.778	0.451	0.534
x_{1999}	0.539	0.546	0.191	0.262
x_{2000}	0.553	0.560	0.198	0.272
x_{2001}	0.450	0.452	0.143	0.197
x_{2002}	0.448	0.449	0.143	0.196
x_{2003}	0.198	0.219	0.077	0.098
x_{2004}	—	—	—	—
x_{2005}	—	0.320	—	—
x_{2006}	0.490	0.537	0.209	0.265
MSY	515	418	829	720
MSYL	0.246	0.247	0.245	0.246
-ln *L*: Total	-4.270	-3.186	-6.324	-4.866
-ln *L*: CPUE	-0.569	-1.243	-3.643	-3.106
-ln *L*: Acoustic survey	2.275	2.921	0.281	0.555
ln *L*: year bias *x*	-3.248	-2.451	-0.001	0.630
-ln *L*: prior on *M*	-2.923	-2.885	-2.945	-2.943
-ln *L*: prior on q^{AC}	0.196	0.472	-0.016	-0.002

Table 10. Estimates obtained when various models are fitted to the available index of Namibian orange roughy for the *Hotspot* aggregation, where the standardised CPUE series are equivalent to the "zero" method as there are no gaps in the data (Brandão and Butterworth 2002b and 2006). The estimates shown are for the pre-exploitation orange roughy (recruited=mature) abundance (B_0), the natural mortality (M), the current stock biomass (B_{2006}) and stock depletion (B_{2006}/B_0) at the beginning of the fishing year 2006, the commercial CPUE index catchability coefficient (q^{CPUE}), the standard deviation for the standardised CPUE series (σ^{CPUE}), the estimated proportion of the stock present each year (x_{1994}, …, x_{2004}), the maximum sustainable yield (MSY), the maximum sustainable yield level (MSYL) and the negative of the log likelihood (as well as its different components). Biomass units are tons.

Parameter estimates	"Old" basecase $(\mu_x = 0.6; \sigma_x = 0.2)$	"New" basecase $(\mu_x = 0.5; \sigma_x = 0.25)$	"Alternative" case $(\mu_x = 0.55; \sigma_x = 0.25)$
B_0	4 147	4 156	4 156
M	0.052	0.051	0.051
B_{2006}	431	427	427
B_{2006}/B_0	0.104	0.103	0.103
q^{CPUE} $(\times 10^5)$	107.4	107.1	107.1
σ^{CPUE}	0.352	0.353	0.354
x_{1994}	0.796	0.796	0.796
x_{1995}	0.766	0.766	0.766
x_{1996}	0.717	0.717	0.717
x_{1997}	0.646	0.646	0.646
x_{1998}	0.681	0.681	0.681
x_{1999}	0.630	0.630	0.630
x_{2000}	0.528	0.528	0.528
x_{2001}	0.586	0.586	0.586
x_{2002}	0.656	0.656	0.656
x_{2003}	0.516	0.516	0.516
x_{2004}	0.527	0.527	0.527
x_{2005}	—	—	—
x_{2006}	—	—	—
MSY	102	101	101
MSYL	0.240	0.240	0.240
-ln *L*: Total	-14.587	-10.826	-11.523
-ln *L*: CPUE	-5.978	-5.931	-5.931
ln *L*: year bias *x*	-5.667	-1.951	-2.648
-ln *L*: prior on *M*	-2.942	-2.944	-2.944

Table 11. Summary of deterministic projection information, giving MSY estimates and approximate medium term sustainable yield (SY) estimates based upon Figs. 6–9, for the intermittent aggregation model. The SY estimates reflect depletion to about 0.4 after 35 years for resources estimated to be above MSYL, and maintaining current abundance for those below MSYL. Values in parentheses reflect results given a year previously in Brandão and Butterworth (2006).

	Current depletion B_{2006}/B_0 (B_{2005}/B_0)	**Intermittent aggregation model**	
		MSY	**SY**
Johnies (“Old”basecase)	0.12 (0.11)	277 (291)	250 (250)
***Johnies* (*“New” basecase*)**	0.77 (0.63*)	1 386 (838*)	1 800 (1 000*)
***Frankies* (“Old”basecase)**	0.65 (0.64)	746 (762)	900 (900)
***Frankies* (“New”basecase)**	0.76	1 132	1 400
***Rix* (“Old”basecase)**	0.65 (0.58)	515 (440)	600 (500)
***Rix* (“New”basecase)**	0.78	829	1 100
Hotspot	0.10 (0.08)	102 (100)	100 (100)
Total (“Old”basecase)		1 640 (1 593)	1 850 (1 750)
Total (“New” basecase)		3 449	4 400

* Values obtained when fixing q^{AC} = 1.070.

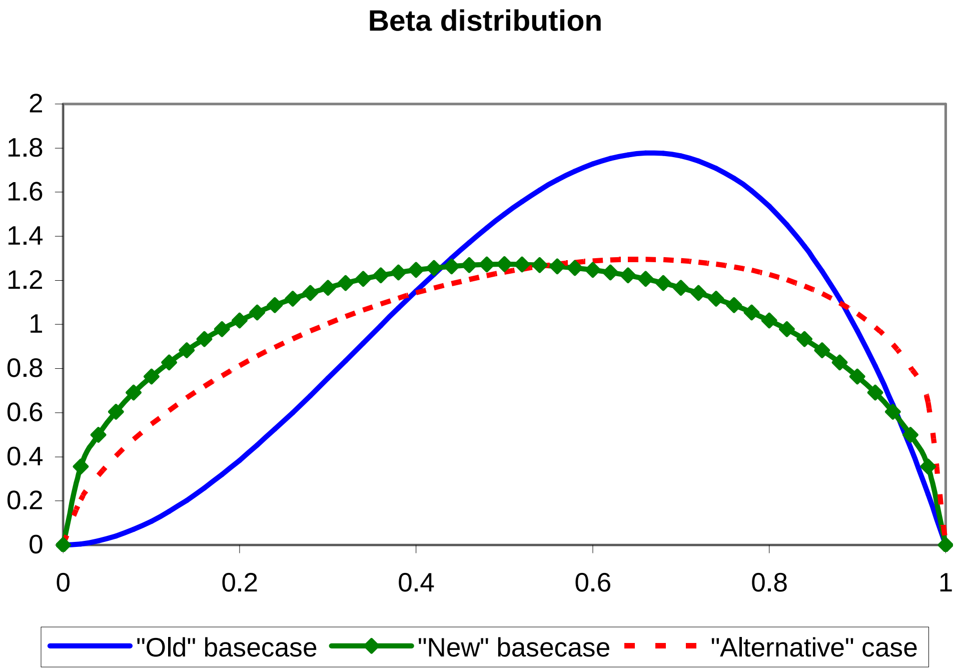

Figure 1. The form of the beta distribution assumed for the penalty function applied to the proportion of stock present (x_y) in the model for intermittent aggregation for various models presented in this paper.

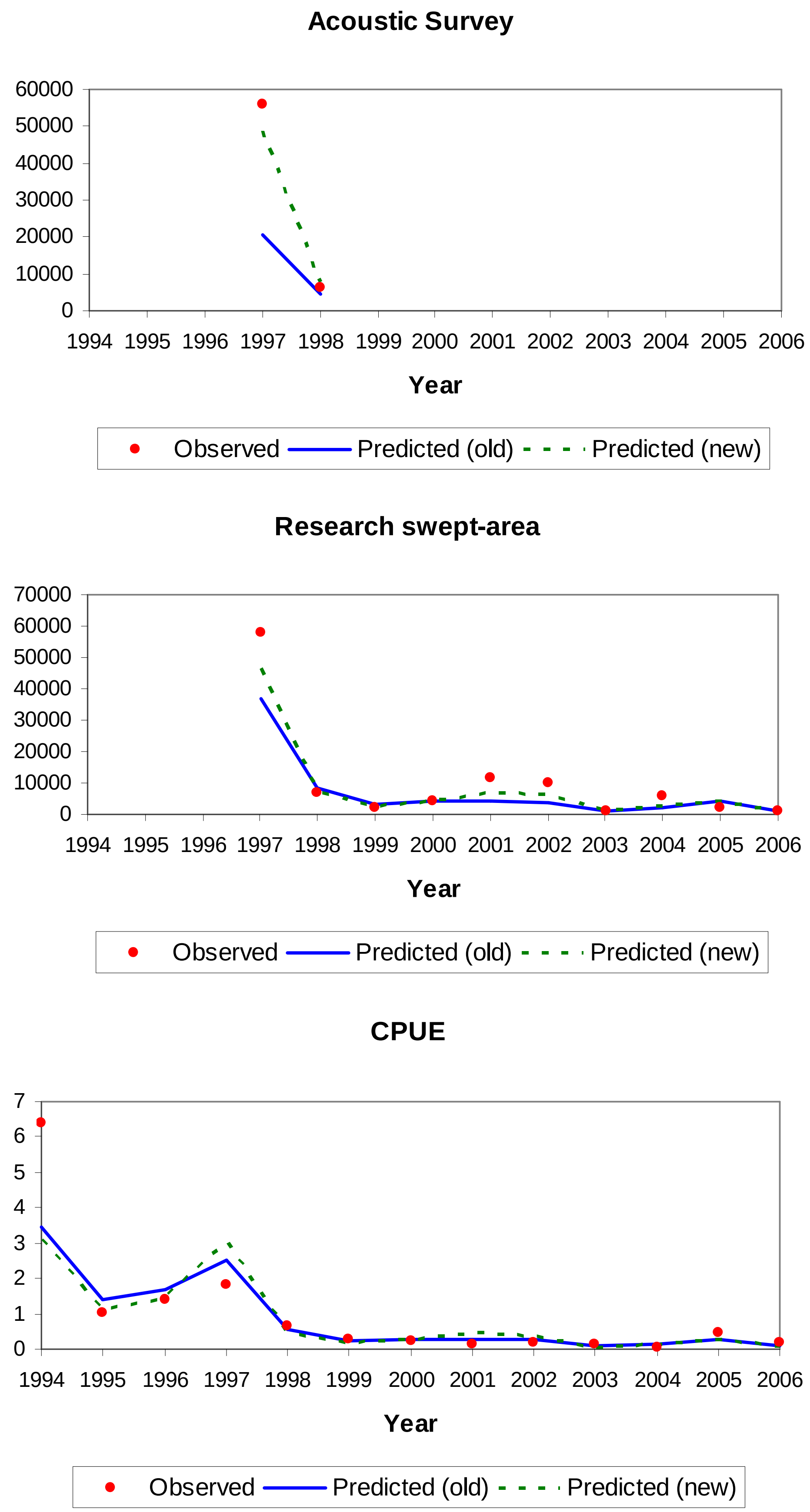

Figure 2. Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Johnies* aggregation when the intermittent aggregation model is fitted to data. Results are shown for the “Old” and “New” basecase models.

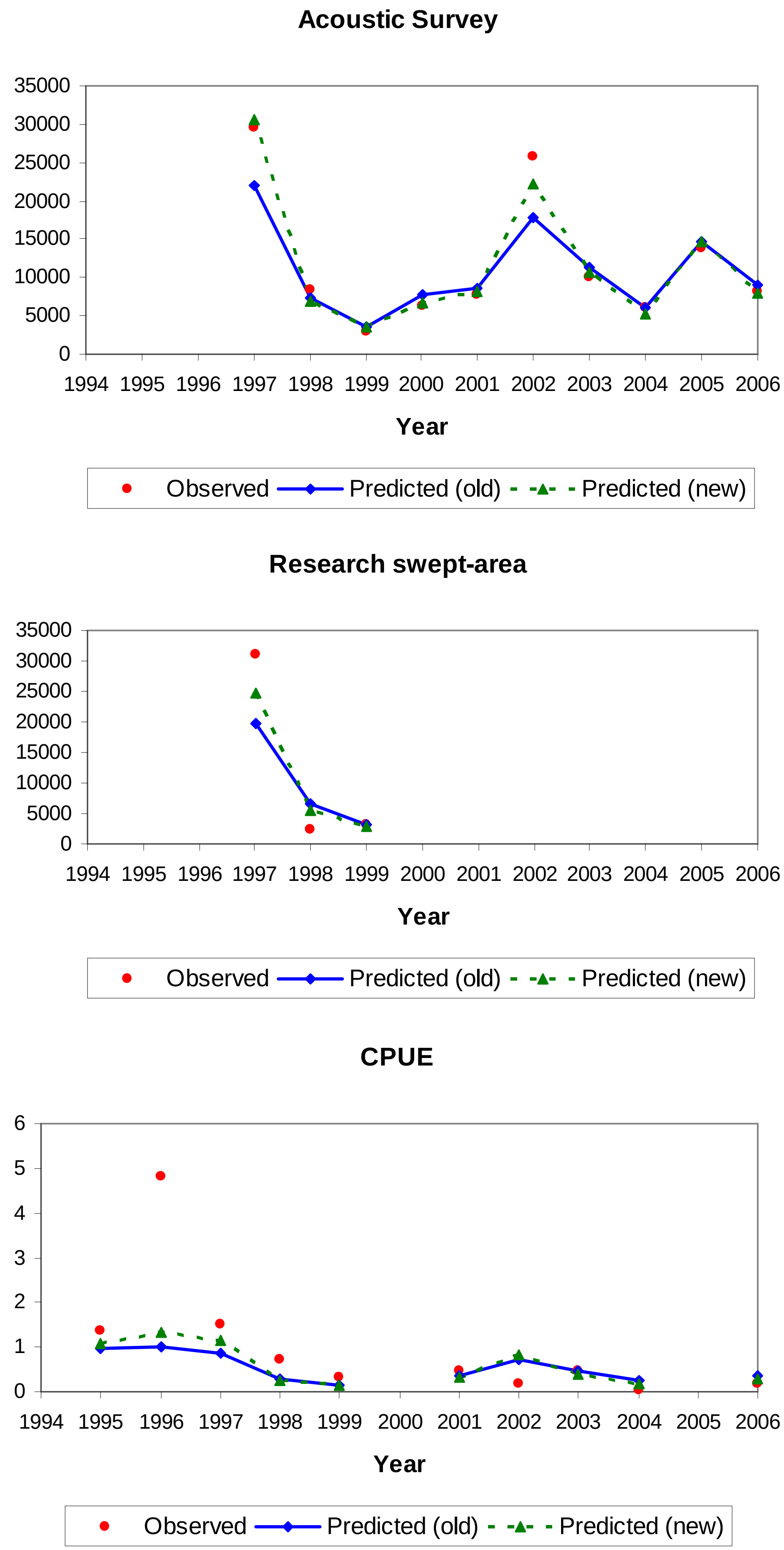

Figure 3. Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Frankies* aggregation when the intermittent aggregation model is fitted to data. Results are shown for the "Old" and "New" basecase models.

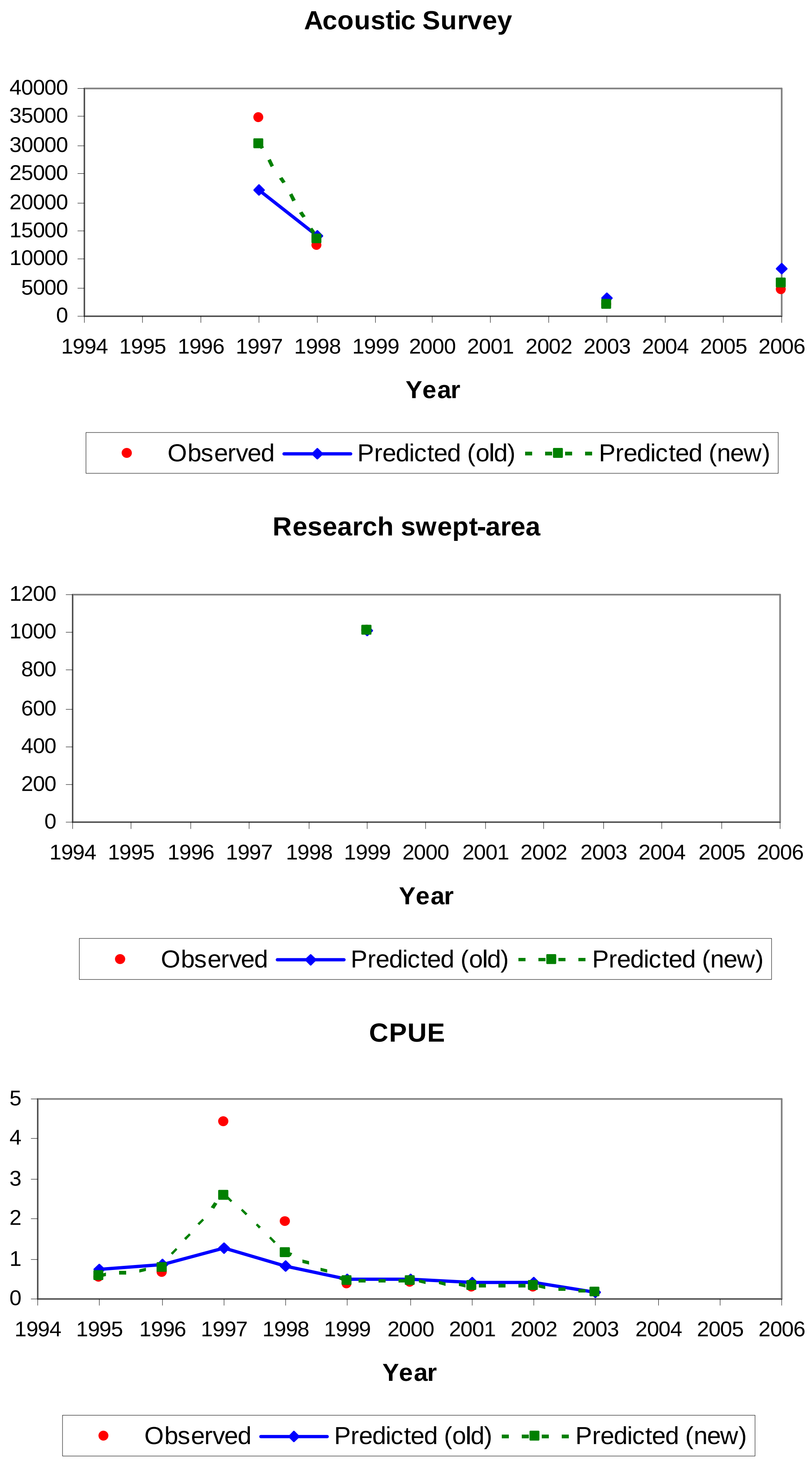

Figure 4. Observed and predicted values for each of the available indices of abundance of Namibian orange roughy for the *Rix* aggregation when the intermittent aggregation model is fitted to data. Results are shown for the "Old" and "New" basecase models. Note that given only one research swept area estimate, the model estimates the corresponding q^{SA} value so that the observed and predicted values match exactly.

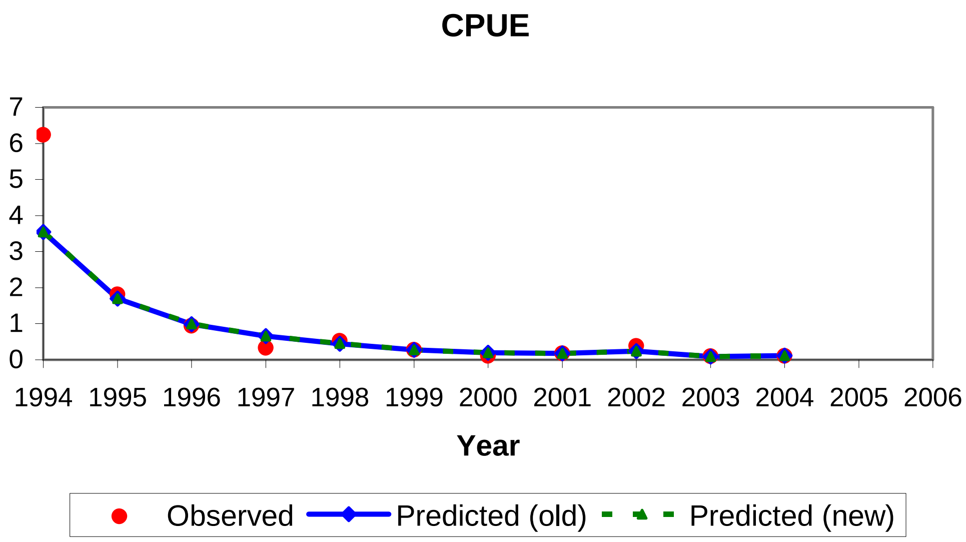

Figure 5. Observed and predicted values for the available index of abundance of Namibian orange roughy for the *Hotspot* aggregation when the intermittent aggregation model is fitted to the data. Results are shown for the "Old" and "New" basecase models.

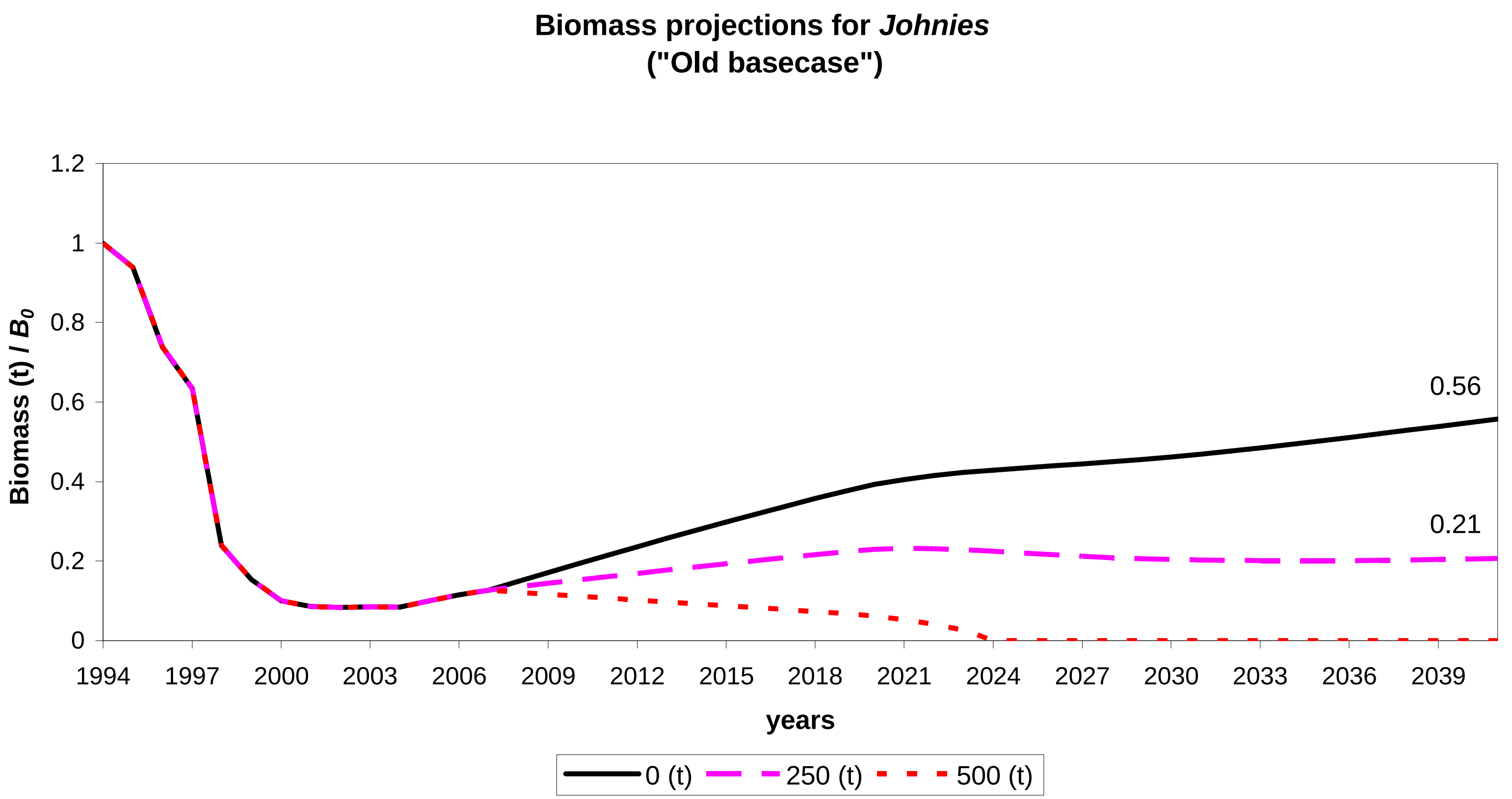

Figure 6a. Thirty five year projections of the orange roughy stock for the *Johnies* aggregation under the scenario of the intermittent aggregation model for the "Old" basecase model. Results for various levels of future constant catch are shown. The figure at the right end of a trajectory is the stock depletion after 35 years.

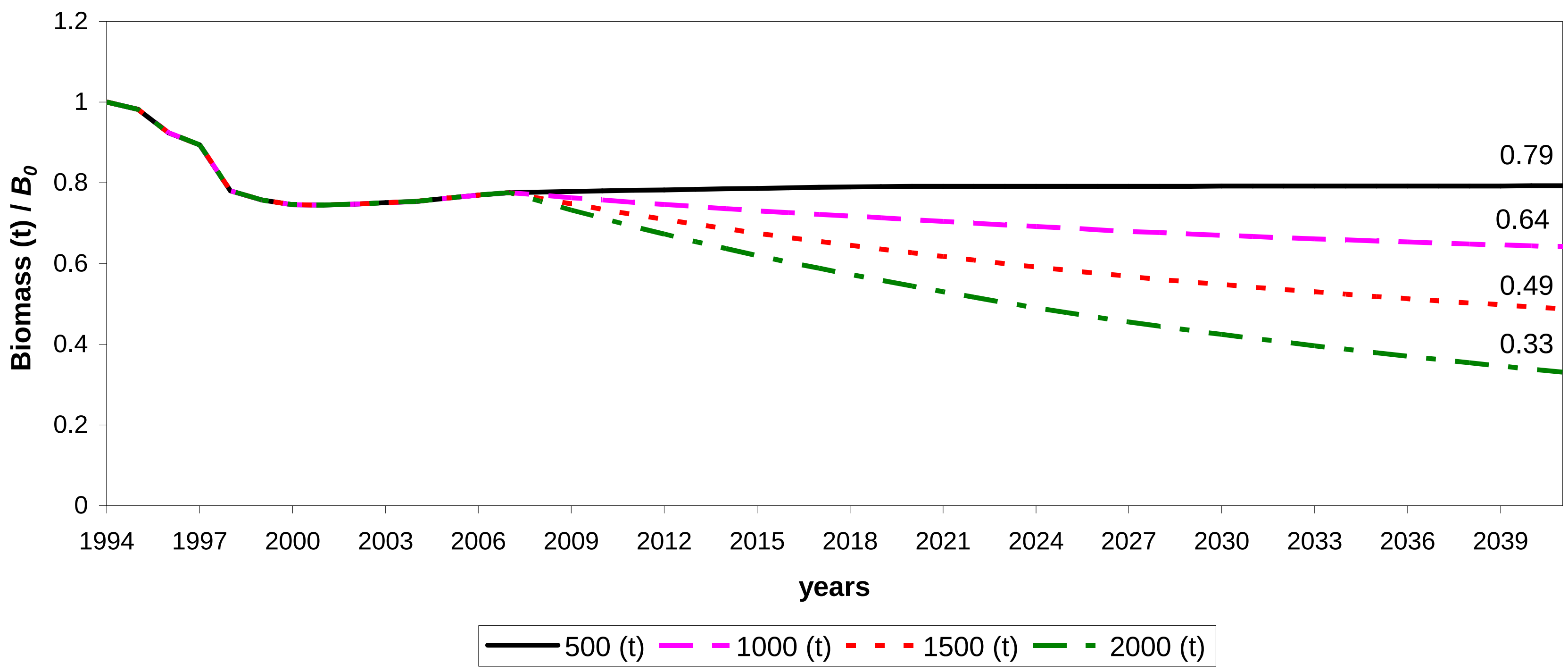

Figure 6b. Thirty five year projections of the orange roughy stock for the *Johnies* aggregation under the scenario of the intermittent aggregation model for the "New" basecase model. Results for various levels of future constant catch are shown. The figure at the right end of a trajectory is the stock depletion after 35 years.

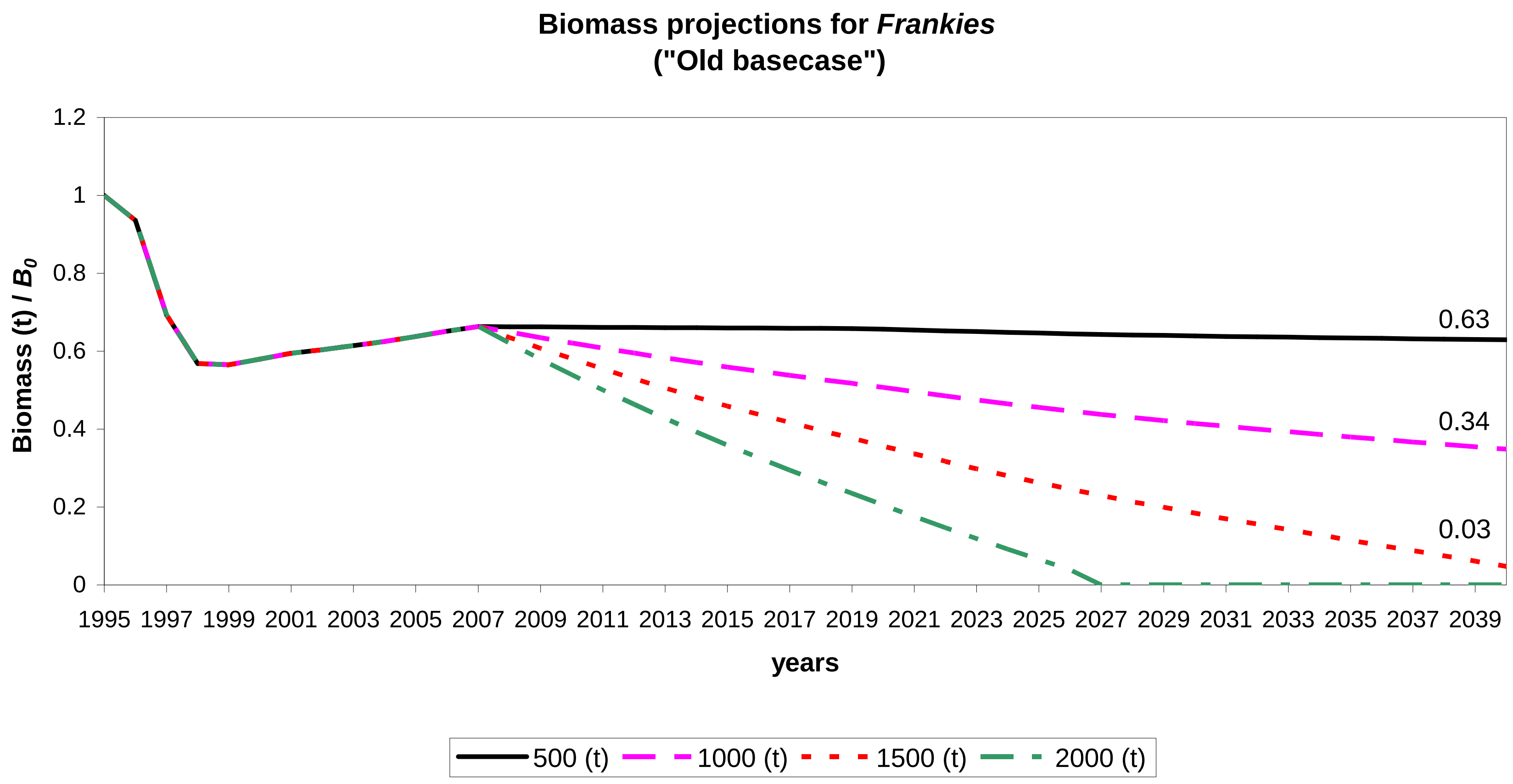

Figure 7a. Thirty five year projections of the orange roughy stock for the *Frankies* aggregation under the scenario of the intermittent aggregation model for the "Old" basecase model. Results for various levels of future constant catch are shown. The figure at the right end of a trajectory is the stock depletion after 35 years.

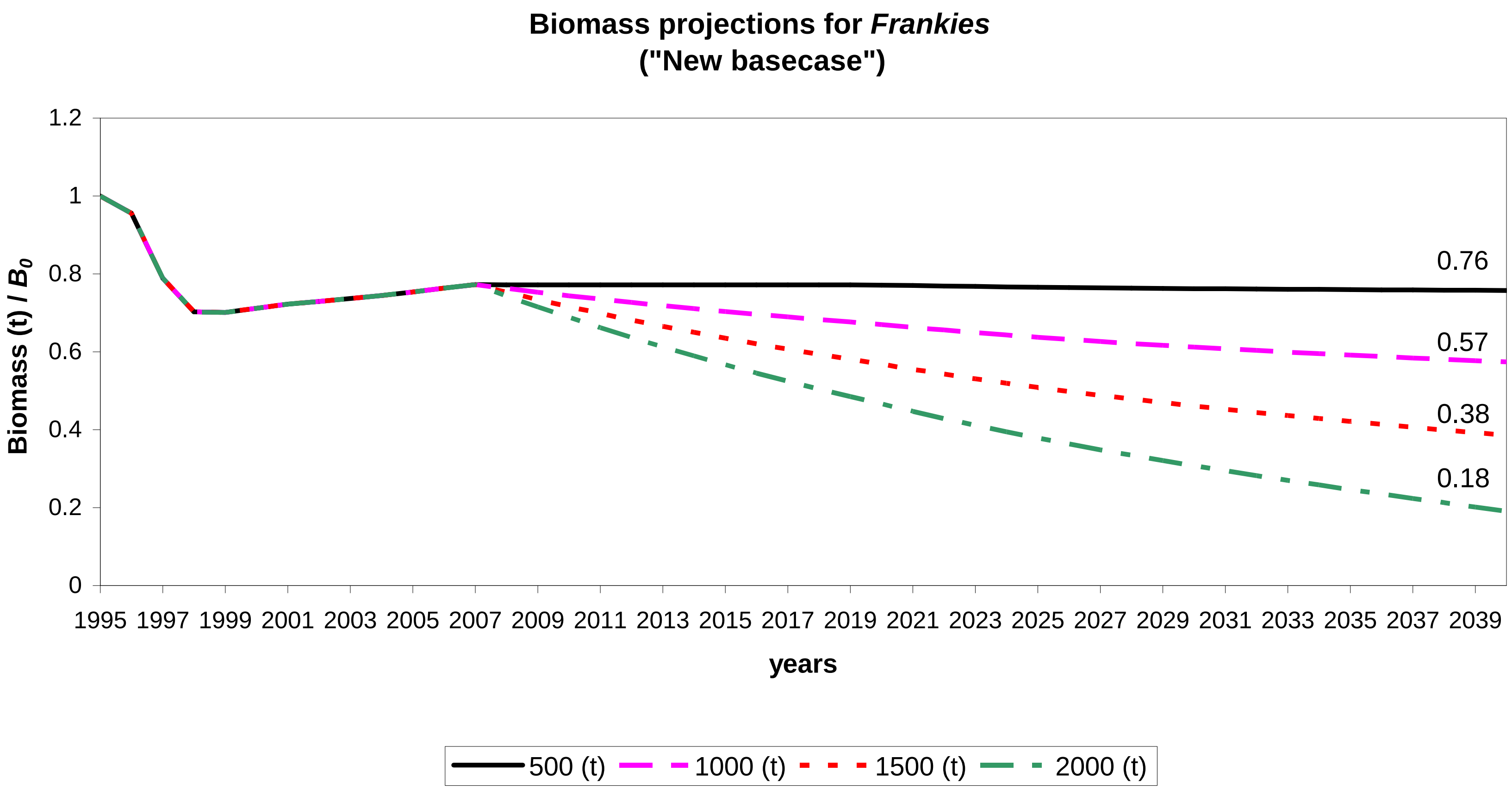

Figure 7b. Thirty five year projections of the orange roughy stock for the *Frankies* aggregation under the scenario of the intermittent aggregation model for the "New" basecase model. Results for various levels of future constant catch are shown. The figure at the right end of a trajectory is the stock depletion after 35 years.

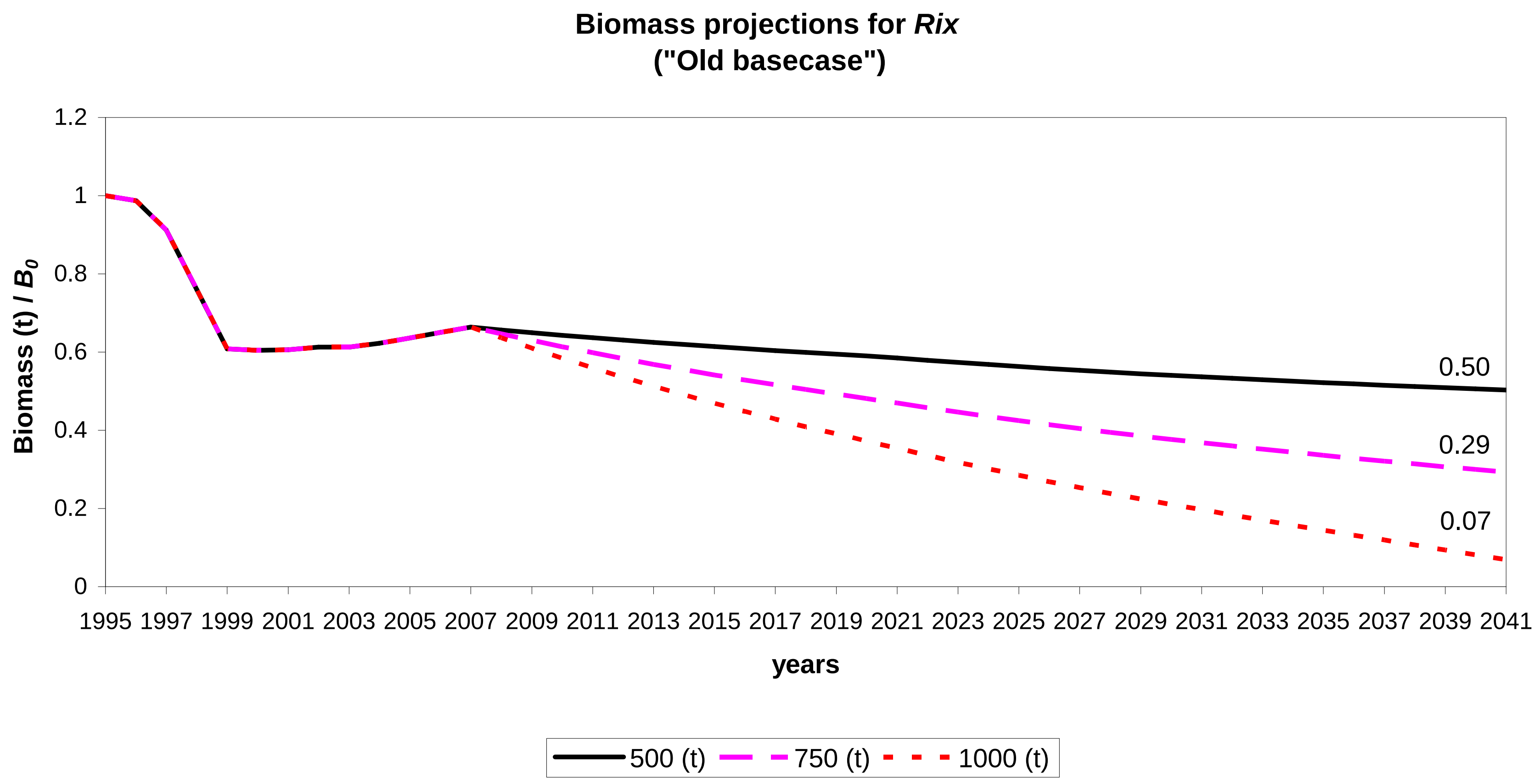

Figure 8a. Thirty five year projections of the orange roughy stock for the *Rix* aggregation under the scenario of the intermittent aggregation model for the "Old" basecase model. Results for various levels of future constant catch are shown. The figure at the right end of a trajectory is the stock depletion after 35 years.

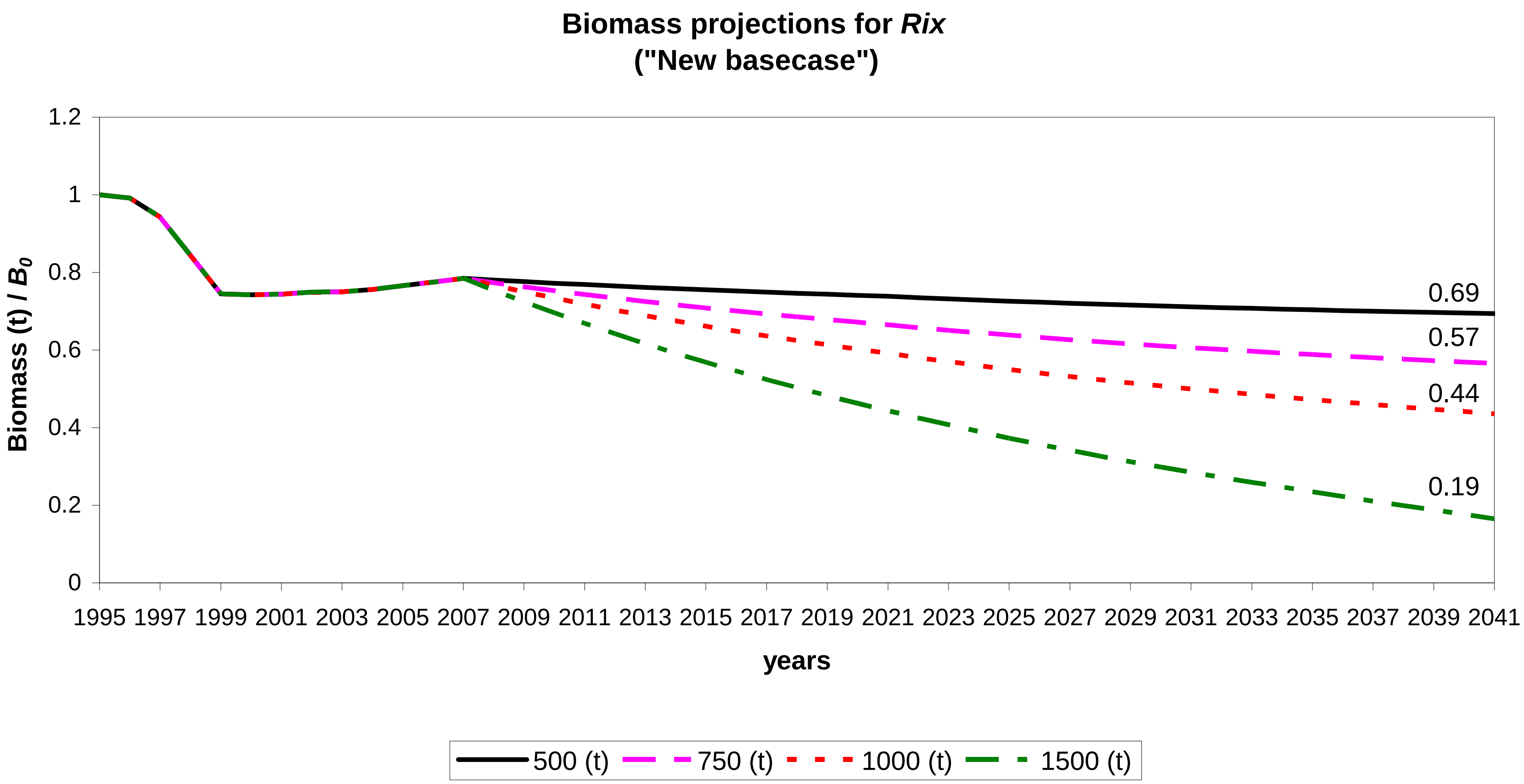

Figure 8b. Thirty five year projections of the orange roughy stock for the *Rix* aggregation under the scenario of the intermittent aggregation model for the "New" basecase model. Results for various levels of future constant catch are shown. The figure at the right end of a trajectory is the stock depletion after 35 years.

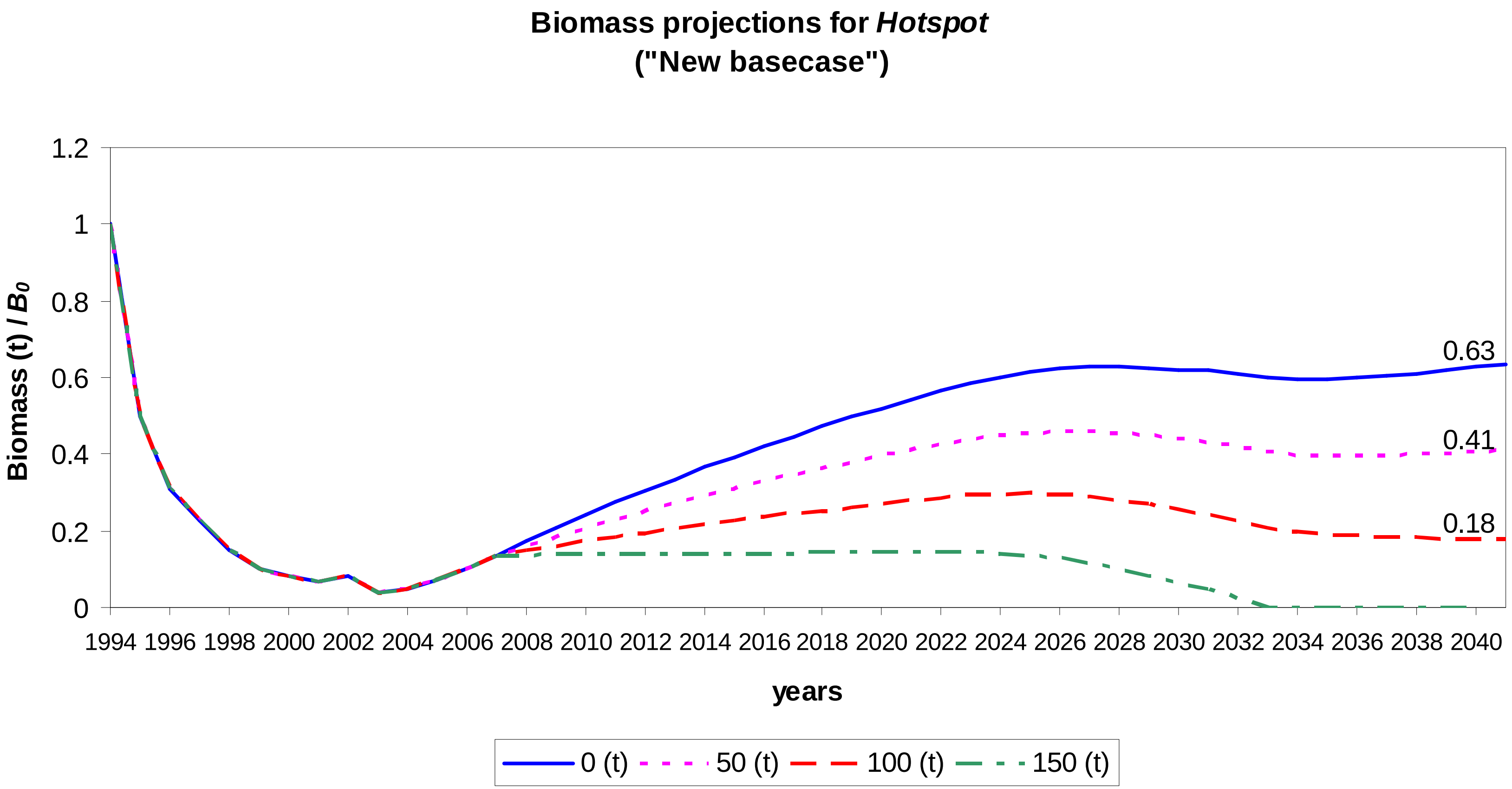

Figure 9. Thirty five year projections of the orange roughy stock for the *Hotspot* aggregation under the scenario of the intermittent aggregation model for the "New" basecase model. Results for various levels of future constant catch are shown. The figure at the right end of a trajectory is the stock depletion after 35 years.

Appendix 1

Bias factors applied to target acoustic indices of absolute abundance of orange roughy

The following table gives the latest bias factor distributions for the acoustic survey estimates of biomass (Boyer and Hampton 2001).

Table A1.1 Bias factor distributions for the acoustic orange roughy survey.

Factor	Minimum	Likely Range	Maximum	Nature
Target strength (experimental error)	0.50	0.75 – 1.25	1.50	Centred on 1.0. Systematic between years
Target strength (length dependency)	1.00	1.10 – 1.20	1.30	Centred on 1.15. Systematic between years
Dead zone (including bottom slope and transducer tilt)	1.10	1.30 – 1.70	1.90	Centred on 1.50. Random between years
Calibration (beam factor)	0.80	0.90 – 1.10	1.25	Centred on 1.0. Systematic between years
Calibration (on-axis sensitivity)	0.90	0.95 – 1.05	1.10	Centred on 1.0. Random between years
Absorption coefficient	0.95	0.98 – 1.02	1.05	Centred on 1.0. Systematic between years
Weather	0.90	1.05 – 1.10	1.25	Centred on 1.075. Random between years
Non-homogeneous aggregations	0.50	0.85 – 0.95	1.00	Centred on 0.75 Random between years
Vessel calibration (if not *Nansen*)	0.8	0.90 – 1.10	1.20	Centred on 1.0. Random between years
Sampling error (CV)		See Table 2a		Aggregation specific. Random between years

Appendix 2

Deterministic Age Structured Production Model (ASPM) for orange roughy

The model is based on the age-structured model presented in Francis *et al*. (1995), which was used to model the population dynamics of orange roughy on the Chatham Rise, New Zealand, and was applied previously to the Namibian orange roughy by, *inter alia*, Branch (1998).

Population dynamics

$$N_{y+1,0} = R(B^{sp}_{y+1}) \qquad \text{(A2.1)}$$

$$N_{y+1,a+1} = (N_{y,a} - C_{y,a})e^{-M} \qquad 0 \le a \le m\text{-}2 \qquad \text{(A2.2)}$$

$$N_{y+1,m} = (N_{y,m} - C_{y,m})e^{-M} + (N_{y,m-1} - C_{y,m-1})e^{-M} \qquad \text{(A2.3)}$$

where:

$N_{y,a}$ is the number of orange roughy of age *a* at the start of year *y*,

$C_{y,a}$ is the number of orange roughy of age *a* taken by the fishery in year *y*,

$R(B^{sp})$ is the Beverton-Holt stock-recruitment relationship described by equation (A2.10) below,

B^{sp} is the spawning biomass at the start of year *y*,

M is the natural mortality rate of fish (assumed to be independent of age), and

m is the maximum age considered (i.e. the “plus group”).

Note that in the interests of simplicity this approximates the fishery as a pulse fishery at the start of the year. Given that orange roughy is relatively long-lived with low natural mortality, such an approximation would seem adequate.

The number of fish of age *a* caught in year *y* is given by:

$$C_{y,a} = N_{y,a}S_aF_y \qquad \text{(A2.4)}$$

where:

F_y is the proportion of the resource above age *a* harvested in year *y*, and

S_a is the commercial selectivity at age *a* (assumed to be knife-edge so that $S_a = 0$ for $a < a_r$ and $S_a = 1$ for $a \ge a_r$.

The mass-at-age is given by the combination of a von Bertalanffy growth equation $\ell(a)$ defined by constants ℓ_∞, κ and t_0 and a relationship relating length to mass. Note that ℓ refers to standard length.

$$\ell(a) = \ell_\infty [1 - e^{-\kappa(a-t_0)}] \quad \text{(A2.5)}$$

$$w_a = c\ell(a)^d \quad \text{(A2.6)}$$

where:

w_a is the mass of a fish at age a.

Given knife-edge recruitment to the fishery, and assuming uniform selectivity for ages $a \geq a_r$, the total catch by mass (C_y) in year y is given by:

$$C_y = \sum_{a=a_r}^{m} w_a C_{y,a} = \sum_{a=a_r}^{m} w_a F_y N_{y,a} \quad \text{(A2.7)}$$

where:

a_r is the age at recruitment to the fishery (assumed equal to the age at maturity (a_m) for these orange roughy populations).

Equation (A2.7) can be re-written as:

$$F_y = \frac{C_y}{\sum_{a=a_r}^{m} w_a N_{y,a}} \quad \text{(A2.8)}$$

Stock-recruitment relationship

The spawning biomass in year y is given by:

$$B_y^{sp} = \sum_{a=1}^{m} w_a f_a N_{y,a} = \sum_{a=a_m}^{m} w_a N_{y,a} \quad \text{(A2.9)}$$

where

f_a is the proportion of fish of age a that are mature (assumed to be knife-edge at age a_m).

The number of recruits at the start of year y is assumed to relate to the spawning biomass at the start of year y, B_y^{sp}, by the Beverton-Holt stock-recruitment relationship (assuming deterministic recruitment):

$$R(B_y^{sp}) = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}}. \quad \text{(A2.10)}$$

The values of the parameters α and β can be calculated given the initial spawning biomass B_0^{sp} and the steepness of the curve *h*, using equations (A2.11)–(A2.15) below. If the initial (and pristine) recruitment is $R_0 = R(B_0^{sp})$, then steepness is the recruitment (as a fraction of R_0) that results when spawning biomass is 20% of its pristine level, i.e.:

$$hR_0 = R(0.2B_0^{sp}) \qquad \text{(A2.11)}$$

from which it can be shown that:

$$h\frac{0.2(\beta + B_0^{sp})}{\beta + 0.2B_0^{sp}}. \qquad \text{(A2.12)}$$

Rearranging equation (A2.12) gives:

$$\beta = \frac{0.2B_0^{sp}(1-h)}{h-0.2} \qquad \text{(A2.13)}$$

and solving equation (A2.10) for α gives:

$$\alpha = \frac{0.8hR_0}{h-0.2}.$$

In the absence of exploitation, the population is assumed to be in equilibrium. Therefore R_0 is equal to the loss in numbers due to natural mortality when $B^{sp} = B_0^{sp}$, and hence:

$$\gamma B_0^{sp} = R_0 = \frac{\alpha B_0^{sp}}{\beta + B_0^{sp}} \qquad \text{(A2.14)}$$

where:

$$\gamma = \left\{ \sum_{a=a_m}^{m-1} w_a e^{-Ma} + \frac{w_m e^{-Mm}}{1-e^{-M}} \right\}^{-1}. \qquad \text{(A2.15)}$$

Past stock trajectory and future projections

Given a value for the pre-exploitation spawning biomass (B_0^{sp}) of orange roughy, and the assumption that the initial age structure is at equilibrium, it follows that:

$$B_0^{sp} = R_0\left(\sum_{a=a_r}^{m-1} w_a e^{-Ma} + \frac{w_m e^{-Mm}}{1-e^{-M}} \right) \qquad \text{(A2.16)}$$

which can be solved for R_0.

The initial numbers at each age a for the trajectory calculations, corresponding to the deterministic equilibrium, are given by:

$$N_{0,a} = \begin{cases} R_0 e^{-Ma} & 0 \le a \le m-1 \\ \dfrac{R_0 e^{-Ma}}{1-e^{-M}} & a = m \end{cases} \tag{A2.17}$$

Numbers-at-age for subsequent years are then computed by means of equations (A2.1)-(A2.4) and (A2.7)-(A2.10) under the series of annual catches given. In cases where equation (A2.8) yields a value of $F_y > 1$, i.e. the available biomass is less than the proposed catch for that year, F_y is restricted to 0.9, and the actual catch considered to be taken will be less than the proposed catch.

The model estimate of the exploitable component of the biomass is given by:

$$B_y^{\exp} = \sum_{a=0}^{m} w_a S_a N_{y,a} = \sum_{a=a_r}^{m} w_a N_{y,a} \tag{A2.18}$$

The likelihood function

The age-structured production model (ASPM) of Brandão and Butterworth (2001) that takes account of all available indices of abundance in the fitting process is used. The likelihood is calculated assuming that the observed abundance indices are lognormally distributed about their expected value:

$$I_y^{method} = \widehat{I}_y^{method} e^{\varepsilon_y} \text{ or } \varepsilon_y = \ln\left(I_y^{method}\right) - \ln\left(\widehat{I}_y^{method}\right), \tag{A2.19}$$

where

I_y^{method} is the abundance index of type *method* for year y, where for example, *method* = *AC*, when dealing with the acoustic abundance index, and so on,

$\widehat{I}_y^{method} = \widehat{q}^{method} \widehat{B}_y^{\exp}$ is the corresponding model estimate, where

- $\widehat{B}_y^{\exp}$ is the model estimate of exploitable biomass of the resource for year y, and
- q^{method} is the catchability coefficient for the abundance indices of type *method*, and

ε_y is normally distributed with mean zero and standard deviation σ (assuming homoscedasticity of residuals).

The negative of the penalised log likelihood (ignoring constants) which is minimised in the fitting procedure is thus:

$$
\begin{aligned}
-\ln L = \; & \frac{1}{2(\sigma_q^{AC})^2}\left(\ln q^{AC} - \ln q^{est}\right)^2 + \ln q^{AC} + \frac{1}{2\sigma_M^2}\left(\ln M - \ln M^{est}\right)^2 + \ln M \\
& + \sum_y^{AC} \frac{1}{2(\sigma_y^{AC})^2}\left(\ln I_y^{AC} - \ln\left(q^{AC} B_y^{\exp}\right)\right)^2 + \sum_y^{SA} \frac{1}{2(\sigma_y^{SA})^2}\left(\ln I_y^{SA} - \ln\left(q^{SA} B_y^{\exp}\right)\right)^2 \qquad \text{(A2.20)} \\
& + \sum_y^{CPUE} \frac{1}{2(\sigma^{CPUE})^2}\left(\ln I_y^{CPUE} - \ln\left(q^{CPUE} B_y^{\exp}\right)\right)^2 + n_{CPUE}\left(\ln \sigma^{CPUE}\right),
\end{aligned}
$$

where

q^{AC} is the remaining multiplicative bias of the acoustic abundance series, whose maximum likelihood estimate is given by:

$$\ln \hat{q}^{AC} = \frac{\left(\sum_y^{AC} \frac{1}{\left(\sigma_y^{AC}\right)^2}\left(\ln I_y^{AC} - \ln \hat{B}_y^{\exp}\right)\right) - 1}{\left(\sum_y^{AC} \frac{1}{\left(\sigma_y^{AC}\right)^2}\right) + \frac{1}{\left(\sigma_q^{AC}\right)^2}},$$

q^{SA} is the catchability coefficient for the research swept area abundance indices, whose maximum likelihood estimate is given by:

$$\ln \hat{q}^{SA} = \frac{\left(\sum_y^{SA} \frac{1}{\left(\sigma_y^{SA}\right)^2}\left(\ln I_y^{SA} - \ln \hat{B}_y^{\exp}\right)\right)}{\left(\sum_y^{SA} \frac{1}{\left(\sigma_y^{SA}\right)^2}\right)},$$

q^{CPUE} is the catchability coefficient for the standardised commercial CPUE abundance indices, whose maximum likelihood estimate is given by:

$$\ln \hat{q}^{CPUE} = \frac{1}{n_{CPUE}} \sum_y^{CPUE}\left(\ln I_y^{CPUE} - \ln \hat{B}_y\right),$$

σ_q^{AC} is the standard deviation of the penalty function applied to q^{AC}, which is input; its value is the CV of the distribution of the product of the systematic bias factor distributions applied to the acoustic abundance indices,

q^{est} is the mean of the penalty function applied to q^{AC}, whose value is taken to be equal to 1 as the distribution of the bias factors for the acoustic estimate have now been defined in such a way that the corrected acoustic estimate is intended to be an unbiased estimate of abundance,

M is the natural mortality rate,

M^{est} is the mean of the penalty function applied to M (i.e. the prior distribution mean), which is input,

σ_M is the standard deviation of the penalty function applied to M (essentially the standard deviation of the prior for log M), which is input,

σ_y^{AC} is the standard deviation of the log acoustic abundance estimate for year y, which is input and is given by:

$$\sigma_y^{AC} = \sqrt{\left(\mathrm{CV}_y^S\right)^2 + \left(\mathrm{CV}_y^R\right)^2}$$

where

CV_y^S is the CV of the sampling error distribution, and

CV_y^R is the CV of the distribution of the product of the random bias factor distributions applied to the acoustic abundance indices,

σ_y^{SA} is the standard deviation of the log research swept area abundance index for year y, which is input and is given by the sampling CV of the research swept area index of relative abundance,

σ^{CPUE} is the standard deviation of the standardised CPUE series, whose maximum likelihood estimate is given by:

$$\hat{\sigma}^{CPUE} = \sqrt{\frac{1}{n_{CPUE}} \sum_{y}^{CPUE} \left(\ln I_y^{CPUE} - \ln \hat{q}^{CPUE} \hat{B}_y^{\exp}\right)^2}$$

I_y^{AC} is the acoustic series estimate for year y,

I_y^{SA} is the research swept area series index for year y,

I_y^{CPUE} is the standardised CPUE series index for year y, and

n_{CPUE} is the number of data points in the standardised CPUE abundance series.

The estimable parameters of this model are q^{AC}, q^{SA}, q^{CPUE}, B_0, σ^{CPUE} and M, where B_0 is the pre-exploitation mature biomass.

In an alternative model to test the comparability of the yearly index estimates of abundance within this framework, an estimable multiplicative bias factor x_y is included in the model, so that the various terms in equation (A2.20) become:

$$\left(\ln I_y^{method} - \ln\left(x_y\ q^{method}\ B_y^{\exp}\right)\right)^2 \qquad \text{(A2.21)}$$

This x factor allows for the possibility that not all the orange roughy belonging to an aggregation collect at that site each year.

The results of the hydroacoustic survey carried out in 2002 in *Frankies* (closed to commercial fishing since 1999) show an index of abundance for 2002 that is in the region of the 1997 estimate (Table 2a and b) indicating that the low indices of abundance observed in years subsequent to 1997 cannot be interpreted as purely fishing down of the population, but instead that variable aggregation of the stock occurs from year to year. Brandão and Butterworth (2003) used this signal in one of the indices for the *Frankies* aggregation to model intermittent aggregation of the orange roughy stock. A penalty function applied to the proportion of stock present (x_y) has also been introduced in the model for intermittent aggregation. As the x_y proportions lie between 0 and 1, this penalty function implies the assumption that the x_y proportions are assumed to follow a beta distribution which is restricted to this range. Therefore the following term is added to the negative of the log likelihood function given in equation (A2.20) in which the various terms are given by equation (A2.21):

$$-\left[N\left\{\ln\Gamma(\alpha+\beta)-\left[\ln\Gamma(\alpha)+\ln\Gamma(\beta)\right]\right\}+\sum_{y=1994}^{2006}\left\{(\alpha-1)\ln\left(x_y\right)+(\beta-1)\ln\left(1-x_y\right)\right\}\right] \qquad \text{(A2.22)}$$

where:

- N is the total number of years considered in the assessment (N = 2006-1994+1),
- α is a parameter of the beta distribution, such that $\alpha > 0$,
- β is a parameter of the beta distribution, such that $\beta > 0$.